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13. ABSTRACT (Maximum 200 words)

This grant was for the purchase of a laser system and digital cameras. A Coherent Infinity XPO laser system has been acquired and installed at the Georgia Tech Low Speed Wind Tunnel as planned. A Roper Scientific ES 1.0 dual frame digital camera has been acquired to capture short-time-scale changes, and a Silicon Mountain Designs 6M3P digital camera was acquired to perform high-resolution imaging. Experiments to capture details of rotorcraft tip vortices using this system are proceeding as planned. To perform phosphorescence imaging, various food-grade phosphorescent materials have been selected and tested to capture time-scales of phosphorescence decay; these tests are continuing. Fiber-optic coupling of the beams from this laser was pursued, and fibers were successfully coupled to the beams for low power settings. This approach was temporarily abandoned in favor of an articulated mirror-tube system to enable operation with higher power levels and lower fiber attrition.

14. SUBJECT TERMS
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Sincerely,
N. M. Komerath

Final Report, Project DAAD 19-99-1-0054

Tunable Solid-State Laser and High Resolution Digital Cameras for Lagrangian Vortex Imaging

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GITAER-EAG-0005

Table of Contents

1. Problem Statement

1.1 Introduction

Capturing the generation and nascent characteristics of rotary-wing vortices in flows with high Reynolds number is of great importance. Recent efforts have made significant progress in resolving these, and have shown that efficient deterministic models can be developed for wake vortices to a high order of accuracy. To resolve such phenomena experimentally to the accuracy needed to answer fundamental questions, techniques are needed which do not depend on Mie scattering or Eulerian data acquisition. The global flowfield of a rotary-wing experiment, on the other hand, can be effectively captured using pulsed light sheets and Mie scattering from particles. This grant was for the purchase of a laser system and high-resolution digital camera to enable measurements to the accuracy needed to answer fundamental questions about vortex flows. This laser-camera system is a versatile probe for unsteady, vortex-dominated flows, and provides an improvement of more than two orders of magnitude in the capability to quantify flows in a large wind tunnel. It enables Lagrangian diagnostics of complex flows using microsecond-scale fluorescence and millisecond-scale phosphorescence. It will also be utilized to obtain spatially and temporally resolved velocity fields over large areas and volumes, to the accuracy needed to capture shear and rotation. The 1064nm beam from the pulsed Nd-YAG laser is frequency doubled to 532nm for Mie scattering diagnostics. The beam can also be frequency tripled and used to pump an Optical Parametric Oscillator (OPO). The output of the OPO is tunable from ultraviolet to red portion of the spectrum. The tunable output enables selection from several fluorescence and phosphorescence lines. The laser has a pulse rate variable from 0+ to 100Hz with pulse energy of 200mJ, with external triggering for rotor-synchronized particle tracking and velocimetry. This system will be used to capture the origin of a rotor tip-vortex and its near-wake structure. Phosphorescence with selective seeding injection will be used to capture the roll-up of the blade-tip boundary layer into the tip-vortex, and directly get velocity profiles. Mie-scattering based photogrammetry will be used to capture the subsequent development of the vortex. The system will also help to perform direct comparisons of various planar velocimetry techniques in a well-documented flowfield possessing the crucial elements of realistic flows. Other research problems that will benefit from the acquisition of this system are missile forebody aerodynamics and low-Reynolds number aerodynamics of micro aerial vehicles.

The primary purpose is to enable resolution of the tip vortex from a rotating blade, to the accuracy needed to answer basic questions about vortex generation. General objectives are:

- Improve the spatial and temporal resolution of diagnostics for unsteady, vortex-dominated flows in a large wind tunnel.
- Enable direct comparison of various techniques used for flow quantification in a single facility, thus improving the dynamic range and accuracy of all the techniques. Do this in an environment where synergistic research and instruction integrates results into learning resources.

- Enable Lagrangian particle tracking; needed to probe boundary layers, vortex cores and other shear layers where visualization is hindered by surface reflections or lack of seeding.

1.2 Capabilities Sought

1.2.1 General Capabilities

The primary capability opened up by the proposed system is that of measuring the generation, core structure and evolution of tip vortices with much greater accuracy than was possible before, in realistic flow environments which incorporate the essential flow phenomena. To do this in airflows, we need alternatives to Mie scattering, because particle inertia is a fundamental source of error in this problem. Analytical and computational abilities are reaching the stage where the basic differences between rotary-wing and fixed-wing vortices can be appreciated: these issues cannot be resolved in slow water flows, or in small wind tunnels.

All of the research problems described below involve precise capture and resolution of phenomena which occur over a wide range of temporal and spatial scales in large rotorcraft test facilities, around models in high-Reynolds number air flows, and around vehicle models executing multi-dimensional maneuvers or maneuvering flight in large wind tunnels. Experiments in such facilities require the coordinated operation of many complex systems, and the facility's productivity must be high. The distances involved are on the order of meters; vibration and dust are realities; spaces are constrained and the flows offer no geometric simplification. Bringing advanced flow diagnostics to such facilities is a challenge: these requirements impose constraints that are generally avoidable in many bench-scale diagnostic facilities where advanced laser diagnostics are used. The flow Reynolds number is high enough to have turbulence both in the freestream and in the boundary layer. Air, rather than water, must be used as the test fluid medium, implying low density and low signal level. The flow velocity is of the order of 10 to 100 meters per second. Rotor frequencies in our test case range from 600 to 2100 rpm (10 to 35 Hz), with the blade chord taking up 12° of the tip path circumference. At 2100 rpm, it thus takes 758 microseconds for a 3" rotor blade tip to pass a point on the tip path circle. The region of interest extends at least 3 chord lengths downstream, which is about 36 degrees of rotor rotation, or 2.86 milliseconds. To get a chordwise resolution of 1% chord, the spatial resolution must be 0.857 mm, but the temporal resolution must be 8.6 microseconds.

1.2.2 Lagrangian Diagnostics of Vortex Origin Using Laser-Induced, persistent emission

Laser-induced fluorescence and phosphorescence are proposed as Lagrangian diagnostics in the flow near the tip of a model rotor blade operating at 35 to 70 revolutions per second in a large wind tunnel. Fluorescence typically lasts microseconds, permitting near-field diagnostics using gas-phase substances injected from specified locations on the blade. Phosphorescence can last several milliseconds, permitting tracking of filament roll-up over a longer distance into the vortex. Here the seedant can be in the freestream ahead of the rotor tip.

In the phosphorescence scenario, the laser flash (3 nanosecond) will excite molecules of a seedant in the airflow (typically, 1μm liquid droplets carrying the active substance) through the laser focal volume at time t_0, when the rotor blade is at a desired phase Ψ_0. The excited molecules emit at a wavelength different from the incident laser pulse. At a selected time Δt after the laser pulse, the shutters of two intensified cameras C1 and C2 open for 100 microseconds, recording the locations of the fluid that are still emitting. Knowing Δt and varying Ψ_0 by setting the laser repetition frequency to be slightly different from the rotor frequency, a series of such image-pairs can be obtained, and converted to a velocity field and vortex structure description.

This technique is proposed to capture the origin and structure of the rotor tip vortex. Thus, for instance, as the images from successive laser shots, at slightly different rotor phases are added to the image, we expect to see a series of dots, each corresponding to a known point of origin, describing the roll-up process and structure of the tip vortex. This process requires excellent cycle-to-cycle repeatability, a feature that has been demonstrated with this rotor set-up in the John J. Harper wind tunnel. In the side-view plane, the dots corresponding to successive laser pulses describe the motion of the flow at different radial locations of origin with respect to the core axis of the tip vortex. This provides an independent check on core velocity. These are proposed to be achieved as follows:

The beam from the tunable XPO, which is pumped by the 355nm (third harmonic) beam from the Nd-YAG system, will be conveyed using an articulated mirror arm to the test section of the tunnel. The beam will be coupled from the articulated arm in to the test section using a focusing lens, which focuses the beam to a waist approximately 0.1mm in diameter. The lens will be mounted on the 2-D traverse in the tunnel and will be placed immediately above or below the rotor blade path, similar to the placement of a laser Doppler velocimeter measuring volume. The laser flash will occur when the desired chordwise section of the blade is passing the measurement volume. The image will be captured at varying times after the flash in a chordwise plane to observe the progress of the fluid that was at the specified chordwise section of the blade tip. Once this speed is generally determined, spanwise cross-flow planes will be imaged from downstream at specified times after the flash, to capture the rest of the information needed to determine the path taken by the excited fluid.

Vortex Core Origin Capture

Two major obstacles to the resolution of vortex core origin and structure are: (1) Particle inertia and (b) Surface light scattering. We will first consider surface scattering, which masks the relatively low signal level from micron-sized seed particles in the boundary layer fluid. A solution to this problem is to use a luminescent seedant such as Fluorescein, which is excited at 490nm and emits at 520nm, and a notch filter. The filter would be selected so that only wavelengths around 520nm are passed. This prevents the camera from being blinded by the laser excitation pulse. Therefore, this method would enable measurements closer to the blade tip boundary layer, providing insights into the shear-layer roll up mechanism during the nascent stages of vortex formation. These measurements are needed to provide a physical proof of the genesis of the core axial velocity and inboard sheet vortex. Alternatively, the blade tip surface can be coated with a medium which screens out the incident wavelength: this is to be explored.

Alternatives to Mie scattering (which requires solid or liquid particles), are needed to solve the seed particle inertia problem which plagues vortex core measurements. The radial acceleration in vortex cores is so high (tens of thousands of "g"s) that the core is generally seen as a "clear eye" even when non-volatile seedants are used. With the clean periodicity achieved in our wind tunnel, [1] measurements show that even when velocity data from 100,000 mineral oil seed particles (typically 1 to 4 micron) are collected at a given measurement point where a tip vortex crosses, not a single data point arrives during the period when the measurement volume is actually inside the vortex core. Where the flow is slightly less periodic, we are able to measure tip vortex core axial velocity (see Fig. 3 from Ref. 11), and have reached axial velocity values up to 40% of the rotor tip speed. The question of particle lag remains: what is the real velocity profile inside the vortex as it is generated? This requires measurement of true fluid velocity, since the finite acceleration time of solid or liquid seed particles allows, as best, an asymptotic answer to this question, with the signal-to-noise ratio decreasing as we try to use smaller particles. A gas-phase seedant would solve this problem. Laser-induced fluorescence and phosphorescence, which produce much less emission intensity than Mie scattering from particles, were heretofore impractical due to the low laser pulse energy and the low signal-to-noise ratio of our commercial grade security cameras. It is possible to target selected packets of fluid, over chosen intervals of time using the Nd-YAG laser, since materials with varying luminescence times can be used. Different materials need different excitation frequencies, which is easily afforded by the Nd-YAG laser. Fluorescence and phosphorescence occur over different time-scales. The same instrumentation can be used for two different diagnostics in the flow field. Laser induced fluorescence occurs over time scales of microseconds. Thus the flow can be frozen to less than a degree of blade motion at 1050rpm. In that time, a fluid packet leaving the blade boundary layer on the lower surface would have traveled a small distance. Thus flow patterns can be frozen in one plane without having to consider effects of out of plane flow and streaking. *We aim to measure velocity profiles in selected planes directly from single-pulse events.*

The precise seedants to be used for fluorescence and phosporescence are unspecified pending clear determination of their handling characteristics (i.e., how to ensure safety in the large-tunnel environment). In the early 1980s, we refrained from using the fashionable rotor-tip / shear layer seeding technique using Titanium Tetrachloride ($TiCl_4$ + $2H_2O \leftrightarrow TiO_2 + 4HCl$) and have shown high-fidelity wake imaging using non-toxic seeding in large facilities. Individual seedants will be tested with the laser to study the signal level and concentrations needed, and handling aspects, before usage in the large tunnel.

Photogrammetry combined with Phosphorescence Imaging

A typical phosphorescence scenario is shown in Figure 1. The phosphorescent seeding can be injected into the flow-field either in the flow itself or the blade tips. When the laser beam hits the seeding at a selected place, the phosphorescence emission is captured using cameras in 3 planes. The phosphorescing fluid packet illuminates the Lagrangian path lines of the flow. The origin of the path lines can be located with high precision, by just locating the probe volume appropriately. Lagrangian path lines originating at points in the blade boundary layer on the pressure side of the blade would then provide insight into how the boundary layer fluid rolls up into the vortex core. Accuracy of the traces depends on camera resolution. The cameras for this system supplement two existing 1024 x 1024 digital cameras, to provide the 4-camera system needed for photogrammetry with one redundancy. The 3Kx2K camera will capture planes where the highest resolution is needed.

Velocity Profiles From Phosphorescence

Phosphorescence can also be used to do time-line photography based on the same principles as hydrogen bubble flow visualization done with heated wires in water tunnels. The flow is seeded with a cloud of phosphorescent material. The laser beam is directed along a selected line in the flow, so that all the seeding along the line starts phosphorescing. Three cameras are set up in the flow-field at appropriate locations. The cameras are triggered externally to open a fixed time period after the laser tags a line in the flow. The camera gating duration is set to capture streaks. The deformation of the phosphorescent line with respect to the tagged line will give the velocity profile in 3-dimensions. A schematic is shown in Figure 1. The table below lists the characteristics of a number of commonly available dyes. Note the wide range of excitation frequencies and lifetimes.

Table 1: Characteristics of commercially available dyes. From Refs. 2 - 6

Item	Name of dye	Excitation (nm)	Emission (nm)	Lifetime
1	Flourescein	494	518	4.96ns
2	Alexa 488	495	519	~ 5 ns
3	Rhodamine B	555	580	6.16ns
4	Europium chloride	556	575	0.1 ms
5	Acetophenone	387	~420	~5ms
6	Benzophenone	412	~450	~8ms
7	La Jolla Blue	680	700	~ 4.5ns

The acquisition procedure is quite efficient. The laser flashes will be set to occur nominally at 70 times per second to coincide with each blade passage of the two blades, and then the time between flashes will be increased by 8.6 microseconds so that each blade passage is illuminated 1% of chord downstream of the previous flash. The fluorescence measurement region will be kept constant and the images recorded for about 30 seconds. The plane is then moved downstream in steps so that the entire process is repeated for 30 seconds at each such measurement station.

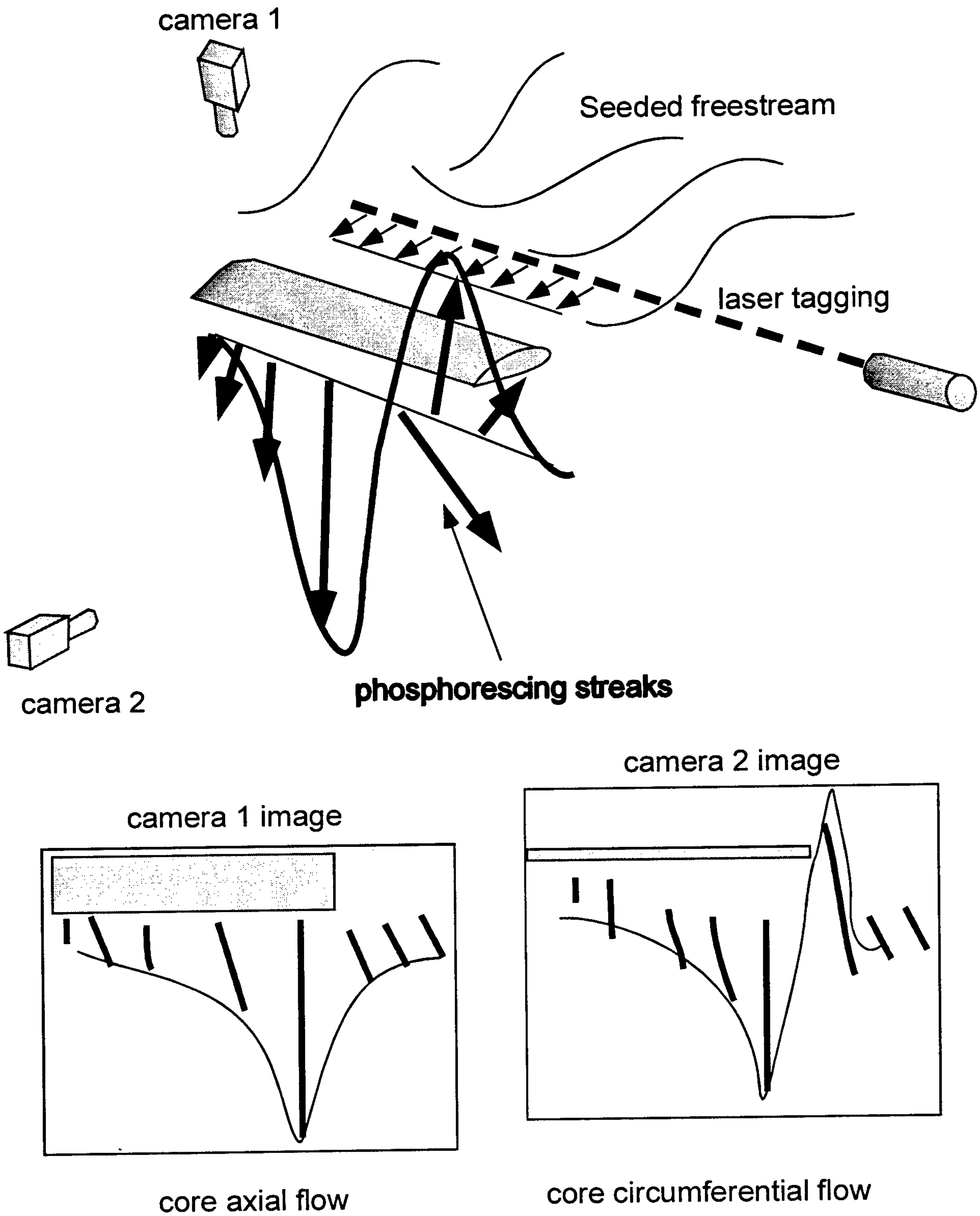

Figure 1. Measurement of velocity profiles using phosphorescence tagged time-lines

On videotape, this sequence will resemble a very slow motion of the rotor blade. Our operating experience with this 2-bladed rotor and visualizations of its wake show that the rotor speed control and the flow quality are quite adequate to achieve the periodicity needed to make this process work. The recorded video will be captured as movies into a Pentium III class computer, and sorted according to rotor blade station. By locating the centroid of the light intensity, the trajectory of the fluid element originating from each chordwise station will be captured. At the end, these will be reconstructed into a 3-D flowfield, with colors used to distinguish filament trajectories from each chordwise station. If the intensity level permits, we will attempt to capture the fluid motion using a pair of intensified, time-separated video cameras to determine the in-plane velocity field. This is discussed further in a following section.

1.2.3 Passive Scalar Visualization Using Mie Scattering

In the above problem, Mie scattering from seed particles is easily captured in planes illuminated by a 532nm sheet. The light sheet achievable with this system is an order of magnitude more intense and precise than that from our copper vapor laser (CVL); the pulse energy is as much as 40 times that from the CVL. Thus the scattering intensity from each particle illuminated in the sheet is expected to be 2 to 3 orders of magnitude brighter than from the CVL sheet. Imaging at the distances, flow speeds and time scales of rotor tip vortex development requires much greater pulse energy, and shorter exposure, than what can be obtained with the CVL and home camcorders. We aim for better resolution in imaging the rotor tip vortex core, at tip speeds from 100 to 200m/s.

1.2.4 Spatial Correlation Velocimetry

The fluorescence or phosphorescence images obtained from two time-separated cameras are used to compute the instantaneous in-plane velocity field by direct spatial cross-correlation. When Mie scattering is used, the 532nm beam will be split into two and one beam will be time-delayed to enable double-camera imaging: a suitable delaying mechanism has to be found for this. With the purchased equipment, spatial cross-correlation velocimetry (SCV, [7]) will be performed using the dual frame digital camera. In SCV, we need not resolve particles: thus, the temporal evolution of spatial patterns of fluorescence or phosphorescence, seen by two time-separated gated cameras, can be used for velocity measurement. The high resolution of the cameras provides excellent spatial resolution. This potentially allows extension of the SCV technique down to the smallest scales of turbulence in the flow.

1.2.5 Planar Doppler Velocimetry

The pulse intensity of the requested laser is adequate to enable sensing of the Doppler shift from cross-flow laser sheet images of Mie scattering. Here one of the cameras will be used for the reference image, and the other for sensing the image filtered through a notch filter set at the incident laser frequency. This method has been used at Langley by Gorton et al [8]. Alternately, following the method of Ref. [9], one of the cameras can be used to capture two split images, freeing the other camera to capture another component of the velocity. Cross-flow vortex images permit easy interpretation of flow direction, so that even one camera can be used, with knowledge of the shape and center of the vortex from the image, to capture the 2-component velocity distribution. This is adequate for measuring instantaneous vortex strength, and its changes during, for example, forebody vortex control experiments. One advantage of PDV is that a single laser flash can give the velocity, permitting use of the video-rate laser, rather than a high frequency or double-pulsed laser. The other is that it enables studies of vortices at high tunnel speeds where usual Mie scattering visualization is quite difficult. PDV accuracy gets better as the velocity increases: Ref. [10] cites accuracy better than 2m/s in low-speed flows. Combined with SCV (using the copper vapor laser), we can thus put together a comprehensive diagnostic capability spanning the entire speed range.

2.0 Summary of Results

2.1 System Acquired

The visualization system obtained consists of the Nd:YAG laser, digital cameras, light transmission devices and seed particles. Each of these items will be discussed in detail below.

2.1.1 Coherent Infinity XPO Nd:YAG Laser

The Infinity XPO laser is a diode pumped Nd:YAG laser capable of repetition rates from 0+ to 100Hz. The 1064nm beam is frequency doubled to 532nm and then frequency tripled to 355nm. The 355nm beam is used to pump a BBO crystal. The output of the BBO crystal is tunable over the visible range by varying the incident angle between the BBO crystal and the pump beam. The maximum pulse energy of the tunable beam is approximately 20mJ. The laser can be synchronized to external events via TTL level signals.

2.1.2 Roper Scientific ES 1.0 Dual Frame Digital Camera

To capture short time-scale changes, a Roper Scientific ES 1.0 dual frame digital cameras was acquired. The ES 1.0 is a moderate resolution, 1008 x 1008 pixels, 30 frame-per-second, 10 bit digital camera. Images are transferred from the camera to the host computer using a Bitflow Roadrunner frame grabber. This camera has a unique double exposure mode. In this mode the camera captures two images, with a short delay between them. The minimum delay between the images is on the order of tens of microseconds. In the past we have used two cameras to capture the image pairs. The primary benefit of the ES 1.0 over the two-camera system is that there is only one lens. A single lens ensures that the same focus and aperture setting are used for both of the images. Furthermore, image registry problems due to physical misalignment and parallax are eliminated. One of the advantages of using digital cameras is that they can be triggered to capture an image at an arbitrary time. Therefore, synchronizing with events that are not multiples of 30Hz, such as a rotor, are substantially easier

2.1.3 Silicon Mountain Design 6MP3 Digital Camera

The 6MP3 is an extremely high resolution, 3072 x 2048 pixels, 3 frame-per-second, 12 bit digital camera. A Matrox Meteor Dig II frame grabber is used to transfer the images to the host computer. The 12 bit dynamic range is vital for visualizing the phosphorescent particles. However, if the emission levels are lower than what can be captured at full resolution, this camera can be switched electronically to 2x2, 4x4 or 8x8 binning. Binning sums neighboring pixels on the CCD to achieve higher sensitivity and frame rates at the expense of lower spatial resolution. This mode is extremely useful for low light levels or higher frame rates.

2.1.4 Xybion Intensified Relay Optics

The dynamic range of the ES 1.0 is only 10 bits. It is not capable of binning, so its use in low light situations (such as those that may be encountered in the phosphorescent experiments) may be limited. To compensate for its poor low light sensitivity, Xybion Intensified Relay Optics (IRO) were purchased. These consist of a low-light image intensifier that sits between the camera lens and the camera. Light collected by the lens is amplified by the IRO and then passed to the camera. Gaines between 25,000 and 50,000 are achievable with this intensifier. The IRO uses a third generation image intensifier with extended blue response. The extended blue response gives us excellent sensitivity over the visible range. The IRO's quantum efficiency is approximately 40% across the visible range.

2.1.5 3M Multimode Optic Fibers

The laser must be located outside of the test section due to size and building utility access requirements. Large core multimode optics fibers were obtained to transmit the beam into the test section. The fibers have a core size of 1500 μm and have peak damage threshold of 56 MW. These fibers were successfully coupled to the laser via discrete optics at low power and repetition rates. However, at higher power and repetition rates the fibers failed.

2.1.6 Laser Mechanisms Articulated Arm

Since the optical fibers failed at high power, an articulated arm or "light pipe" was purchased to transmit the beam in to the test section. The articulated arm used mirrors designed to withstand the high power beam. The arm consists of a beam launcher and two rigid pipes approximately 1 m in length. The beam launcher and pipes are connected together using knuckles with three degrees of rotation freedom. Each knuckle contains three mirrors that are positioned so that the beam is always along the centerline of the arm no matter how the arm is oriented. Attached to the end is another knuckle that allows the laser sheet generating optics to be oriented in any direction. The light sheet generating optics consists of a cylindrical lens and a spherical focusing lens. In this configuration, light sheets 3mm in thickness can be obtained.

2.1.7 Natura Phosphorescent Material

Several samples of phosphorescent materials were obtained from Natura Incorporated. Their materials are proprietary formulas based on food-grade components and have reduced toxicity. The peak excitation wavelength for these materials is 360nm. Peak emission is at 518nm. Tests investigating time constants of these materials were conducted using an excitation wavelength of 410nm. The 410nm wavelength was used since it is the lowest wavelength obtainable from the BBO section of the laser. The excitation levels using 410nm light were not bright enough to successfully measure the time constant.

2.2 Current Plans

- Reconfigure the laser to output the 355nm pump beam and measure the time constant of phosphorescent samples.
- Determine the toxicity of the phosphorescent samples
- Use phosphorescent imaging to visualize the vortex formation process on a fixed wing
- Validate phosphorescent imaging velocity measurement technique on a fixed wing

3.0 Publications

None to date: System still in use, experiments planned

4.0 Personnel

- Narayanan M. Komerath, Professor of Aerospace Engineering
- Oliver D. Wong, Doctoral Candiate, Aerospace Engineering
- Raghav Mahalingam, Post Doctoral Research Assistant, Mechanical Engineering

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Appendix A: Original Proposal

CONTENTS

1. REQUEST FOR INSTRUMENTATION

1.1 Abstract

The requested instrumentation is primarily intended to capture the generation and nascent characteristics of rotary-wing vortices in flows with high Reynolds number. Recent efforts have made significant progress in resolving these, and have showed that efficient deterministic models can be developed for wake vortices to a high order of accuracy. To resolve such phenomena experimentally to the accuracy needed to answer fundamental questions, techniques are needed which do not depend on Mie scattering or Eulerian data acquisition. The global flowfield of a rotary-wing experiment, on the other hand, can be effectively captured using pulsed light sheets and Mie scattering from particles. A tunable solid-state Nd-Yag laser and high-resolution digital cameras are proposed. This laser-camera system is a versatile probe for unsteady, vortex-dominated flows, and provides an improvement of more than two orders of magnitude in the capability to quantify flows in a large wind tunnel. It enables Lagrangian diagnostics of complex flows using microsecond-scale fluorescence and millisecond-scale phosphorescence. It will also be utilized to obtain spatially and temporally resolved velocity fields over large areas and volumes, to the accuracy needed to capture shear and rotation. The 1064nm beam from a pulsed Nd-Yag laser is frequency doubled to 532nm for Mie scattering diagnostics. Selectable third-harmonic or fifth-harmonic generators produce beams to pump oscillators whose output is thus tunable from the deep ultraviolet to the infrared. The tunable output enables selection from several fluorescence and phosphorescence lines. The laser has a pulse rate variable from 0+ to 100Hz with pulse energy of 200mJ, with external triggering for rotor-synchronized particle tracking and velocimetry. This system will be used to capture the origin of a rotor tip-vortex and its near-wake structure. Phosphorescence with selective seeding injection will be used to capture the roll-up of the blade-tip boundary layer into the tip-vortex, and directly get velocity profiles. Mie-scattering based photogrammetry will be used to capture the subsequent development of the vortex. The system will also help to perform direct comparisons of various planar velocimetry techniques in a well-documented flowfield possessing the crucial elements of realistic flows. Other research problems that will benefit from the acquisition of this system are missile forebody aerodynamics and low-Reynolds number aerodynamics of micro aerial vehicles. The system will be operated in the facilities of the Experimental Aerodynamics group at Georgia Tech's School of Aerospace Engineering. This group continues to be successful in attracting enthusiastic undergraduate participation and integrating research diagnostics into the undergraduate and graduate curricula, as well as in solving problems in the academic and large-scale industry/ government research environments. Their PhD theses have won peer recognition as being consistently among the best generated by their institution.

1.2 Budget

1. Assumes start date of March 1999.
2. Prices for Coherent Inc. Equipment are based on the quote from Mr. Scott Crane, Sales Engineer, Southeast, scott_crane@cohr.com.
3. Kodak prices are from the Kodak price list.

Item	Description	Cost , $	Source
1	Pulsed Nd-Yag laser system: 40W average power at 1064nm; pulse energy ~ 200 mJ; pulse rate 0 to 100 Hz, 1.5x-diffraction-limit IR beam Coherent Infinity 0166-883-00-208v	111,000	Coherent, Inc. 800-527-3786
2	Second Harmonic Generator to convert 1064nm beam to 532nm; pulse energies ~ 250mJ Coherent 0166-876-00	8,000	Coherent, Inc.
3	Third Harmonic Generator to combine 1064nm and 532nm beams to produce 355nm pump beam.	9,000	Coherent, Inc.
4	355nm pumped BBO Optical Parameter Oscillator, tunable from 420nm to 2300nm.	32,000	Coherent, Inc.
5	Diode Pumped Master Oscillator (spare) exchange	15,000	Coherent, Inc.
6	Camera System: Kodak DCS460 3x12-bit, 2036 x 3060 intensified CCDs(2) with external triggering	64,000	Kodak 800-235-6325
	Total	**239,000**	
	Institutional Cost Sharing	**79,000**	
	Requested Amount	**160,000**	

2. SUPPORTING INFORMATION

2.1. Purpose of the request

1) The primary purpose is to enable resolution of the tip vortex from a rotating blade, to the accuracy needed to answer basic questions about vortex generation. General objectives are:
2) Improve the spatial and temporal resolution of diagnostics for unsteady, vortex-dominated flows in a large wind tunnel.
3) Enable direct comparison of various techniques used for flow quantification in a single facility, thus improving the dynamic range and accuracy of all the techniques. Do this in an environment where synergistic research and instruction integrates results into learning resources.
4) Enable Lagrangian particle tracking, needed to probe boundary layers, vortex cores and other shear layers where visualization is hindered by surface reflections or lack of seeding.

The understanding of vortex-dominated flows has reached a stage where better experimental precision, accuracy and resolution are warranted in unsteady, three-dimensional problems. Over the past 20 years we have refined the ability to perform systematic measurements, using many techniques, on complex flows in large, high-Reynolds number facilities. We collaborate with analytical researchers who can really use the high precision and accuracy of measurements to improve modeling of complex phenomena. We have helped solve problems such as rotor-airframe interaction [1], vortex-surface collisions [2], near-wake structure of a rotor [3,4], control of forebody vortex asymmetry [5,6], suppression of twin-tail buffeting at high angle of attack [7,8], and the capture of transient aerodynamics of the NASA X-38 Crew Return Vehicle [9]. Each of these problems was feared to be non-deterministic, until detailed flow diagnostics resolved the phenomena. We have extended diagnostics developed in our facilities to successful experiments conducted in full-scale facilities around the nation. This approach has enabled surprising gains on an ancient problem: modeling the free wake of a rotor using simple vortex dynamics [4] . Less-advertisable but equally major advances have been made in capturing flows in the tiltrotor vehicle development environment using our techniques. The requested investment is timely: the ambitious goals set in the 1980s have been met. The proposed system aims for an improvement of 3 orders of magnitude over what was possible using the argon ion and copper vapor lasers, and home / commercial security-grade CCD cameras which were used in the above over the past 16 years, as follows:

<u>Laser System</u>

1. Pulse energy of 250-500mJ in the visible range compared to the 5mJ copper vapor laser, thus resulting in 2 orders of magnitude improvement in signal to noise ratio.
2. Pulse repetition rate of 0-100Hz, sufficient to achieve rotor or video synchronization.

3. Pulse width of 2-4ns, (Cu laser has 25-50ns), freezing droplets in the 0.1-1 micron range.
4. Beam width of 5.5mm, (Cu laser: 25mm) with better coherence and mode stability.
5. Tunable from ultraviolet to infrared, enabling laser induced fluorescence and phosphorescence. Individual fluid packets can be "tagged" for Lagrangian tracking of the flow. Short-lifetime fluorescence can reduce the uncertainty in capturing the origin of the tip-vortex filament to less than 1% of a blade chord at 1050rpm. Long-lifetime phosphorescence enables the capture of filament trajectories and velocity profiles.

Camera System
1. 3060 x 2036 digital pixel resolution, compared to the present 640 x 240 half-frame analog VHS resolution, resulting in a factor of 40 in resolution (independent vectors per unit area), when used for Spatial Correlation Velocimetry.
2. 12-bit pixel depth, giving a factor of 16 in the dynamic range over the present 8-bit, needed for flows where the seeding density is highly non-uniform.
3. Elimination of the noise in the D/A and A/D conversions and image compression needed with analog video cameras with frame-grabbers.
4. The Nd-Yag / dual camera system opens up measurement of cross-flow velocity (dominant out of plane flow component) in vortices at up to 60 m/s tunnel speed using Planar Doppler Velocimetry. The use of these capabilities in various projects is described below.

2.2 Capabilities Sought

General Capabilities

The primary capability opened up by the proposed system is that of measuring the generation, core structure and evolution of tip vortices with much greater accuracy than was possible before, in realistic flow environments which incorporate the essential flow phenomena. To do this in air flows, we need alternatives to Mie scattering, because particle inertia is a fundamental source of error in this problem. Analytical and computational abilities are reaching the stage where the basic differences between rotary-wing and fixed-wing vortices can be appreciated: these issues cannot be resolved in slow water flows, or in small wind tunnels.

All of the research problems described below involve precise capture and resolution of phenomena which occur over a wide range of temporal and spatial scales in large rotorcraft test facilities, around models in high-Reynolds number air flows, and around vehicle models executing multi-dimensional maneuvers or maneuvering flight in large wind tunnels. Experiments in such facilities require the coordinated operation of many complex systems, and the facility's productivity must be high. The distances involved are on the order of meters; vibration and dust are realities; spaces are constrained and the flows offer no geometric simplification. Bringing advanced flow diagnostics to such facilities is a challenge: these requirements impose constraints which are generally avoidable in many bench-scale diagnostic facilities where advanced laser diagnostics are used. The flow Reynolds number is high enough to have turbulence both in the freestream and in the boundary layer. Air, rather than water, must be used as the test fluid medium, implying low density and low signal level. The flow velocity is of the order of 10 to 100 meters per second. Rotor frequencies in our test case range from 600 to 2100 rpm (10 to 35 Hz), with the blade chord taking up 3° of the tip path circumference. At 2100 rpm, it thus takes 758 microseconds for a 3" rotor blade tip to pass a point on the tip path circle. The region of interest extends at least 3 chord lengths downstream, which is about 30 degrees of rotor rotation, or 2.38 milliseconds. To get a chordwise resolution of 1% chord, the spatial resolution must be 0.762 mm, but the temporal resolution must be 7.6 microseconds.

2.2.1 Lagrangian Diagnostics of Vortex Origin Using Laser-Induced, persistent emission

Laser-induced fluorescence and phosphorescence are proposed as Lagrangian diagnostics in the flow near the tip of a model rotor blade operating at 35 to 70 revolutions per second in a large wind tunnel. Fluorescence typically lasts microseconds, permitting near-field diagnostics using gas-phase substances injected from specified locations on the blade. Phosphorescence can last several milliseconds, permitting tracking of filament roll-up over a longer distance into the vortex. Here the seedant can be in the freestream ahead of the rotor tip.

In the phosphorescence scenario the laser flash (1 nanosecond) will excite molecules of a seedant in the air flow (typically, 1μm liquid droplets carrying the active substance) through the laser focal volume at time t_0, when the rotor blade is at a desired phase Ψ_0. The excited molecules emit at a wavelength different from the incident laser pulse. At a selected time Δt after the laser pulse, the shutters of two intensified cameras C1 and C2 open for 100 microseconds, recording the locations of the fluid which is still emitting. Knowing Δt and varying Ψ_0 by setting the laser repetition frequency to be slightly different from the rotor frequency, a series of such image-pairs can be obtained, and converted to a velocity field and vortex structure description.

This technique is proposed to capture the origin and structure of the rotor tip vortex. Thus, for instance, as the images from successive laser shots, at slightly different rotor phases are added to the image, we expect to see a series of dots, each corresponding to a known point of origin, describing the roll-up process and structure of the tip vortex. This process requires excellent cycle-to-cycle repeatability, a feature which has been demonstrated with this rotor set-up in the John J. Harper wind tunnel. In the side-view plane, the dots corresponding to successive laser pulses describe the motion of the flow at different radial locations of origin with respect to the core axis of the tip vortex. This provides an independent check on core velocity. These are proposed to be achieved as follows:

The beam from the tunable XPO, which is pumped by the 355nm (third harmonic) beam from the Nd-YAG system, will be conveyed using optical fiber to the test section of the tunnel. A fiber-optic coupler will connect to a focusing lens mounted on the 2-D traverse in the tunnel, and the beam focused down to a waist measuring roughly 0.1mm in diameter. This will be placed immediately above or below the rotor blade path, similar to the placement of a laser Doppler velocimeter measuring volume. The laser flash will occur when the desired chordwise section of the blade is passing the measurement volume. The image will be captured at varying times after the flash in a chordwise plane to observe the progress of the fluid which was at the specified chordwise section of the blade tip. Once this speed is generally determined, spanwise cross-flow planes will be imaged from downstream at specified times after the flash, to capture the rest of the information needed to determine the path taken by the excited fluid.

Vortex Core Origin Capture

Two major obstacles to the resolution of vortex core origin and structure are: (1) Particle inertia and (b) Surface light scattering. We will first consider surface scattering, which masks the relatively low signal level from micron-sized seed particles in the boundary layer fluid. A solution to this problem is to use a luminescent seedant such as Fluorescein, which is excited at 490nm and emits at 520nm, with a filter. This would enable measurements closer to the blade tip boundary layer, providing insights into the shear-layer roll up mechanism during the nascent stages of vortex formation. These measurements are needed to provide a physical proof of the genesis of the core axial velocity and inboard sheet vortex. Alternatively, the blade tip surface can be coated with a medium which screens out the incident wavelength: this is to be explored.

Alternatives to Mie scattering (which requires solid or liquid particles), are needed to solve the seed particle inertia problem which plagues vortex core measurements. The radial acceleration in vortex cores is so high (tens of thousands of "g"s) that the core is generally seen as a "clear eye" even when non-volatile seedants are used. With the clean periodicity achieved in our wind tunnel, [10,11] measurements show that even when velocity data from 100,000 mineral oil seed particles (typically 1 to 4 micron) are collected at a given measurement point where a tip vortex crosses, not a single data point arrives during the period when the measurement volume is actually inside the vortex core. Where the flow is slightly less periodic, we are able to measure tip vortex core axial velocity (see Fig. 3 from Ref. 11), and have reached axial velocity values up to 40% of the rotor tip speed. The question of particle lag remains: what is the real velocity profile inside the vortex as it is generated? This requires measurement of true fluid velocity, since the finite acceleration time of solid or liquid seed particles allows, as best, an asymptotic answer to this question, with the signal-to-noise ratio decreasing as we try to use smaller particles. A gas-phase seedant would solve this problem. Laser-induced fluorescence and phosphorescence, which produce much less emission intensity than Mie scattering from particles, were heretofore impractical due to the low laser pulse energy and the low signal-to-noise ratio of our commercial grade security cameras. It is possible to target selected packets of fluid, over chosen intervals of time using the Nd-YAG laser, since materials with varying luminescence times can be used. Different materials need different excitation frequencies, which is easily afforded by the Nd-YAG laser. Fluorescence and phosphorescence occur over different time-scales. The same instrumentation can be used for two different diagnostics in the flow field. Laser induced fluorescence occurs over time scales of microseconds. Thus the flow can be frozen to less than a degree of blade motion at 1050rpm. In that time, a fluid packet leaving the blade boundary layer on the lower surface would have traveled a small distance. Thus flow patterns can be frozen in one plane without having to consider effects of out of plane flow and streaking. *We aim to measure velocity profiles in selected planes directly from single-pulse events.*

In this proposal, the precise seedants to be used for fluorescence and phosporescence are left unspecified pending clear determination of their handling characteristics (i.e., how to ensure safety in the large-tunnel environment). In the early 1980s, we refrained from using the fashionable rotor-tip / shear layer seeding technique using Titanium Tetrachloride ($TiCl_4 + 2H_2O \leftrightarrow TiO_2 + 4HCl$) and have shown high-fidelity wake imaging using non-toxic seeding in large facilities. Individual seedants will be tested with the laser to study the signal level and concentrations needed, and handling aspects, before usage in the large tunnel.

Photogrammetry combined with Phosphorescence Imaging

A typical phosphorescence scenario is shown in Figure 1. The phosphorescent seeding can be injected into the flow-field either in the flow itself or the blade tips. When the laser beam hits the seeding at a selected place, the phosphorescence emission is captured using cameras in 3 planes. The phosphorescing fluid packet illuminates the Lagrangian path lines of the flow. The origin of the path lines can be located with high precision, by just locating the probe volume appropriately. Lagrangian path lines originating at points in the blade boundary layer on the pressure side of the blade would then provide insight into how the boundary layer fluid rolls up into the vortex core. Accuracy of the traces depends on camera resolution. The cameras being proposed will be supplemented by two existing 1024-1024 digital cameras, to provide the 4-camera system needed for photogrammetry with one redundancy. Each camera has 12-bit pixel depth, and the 3Kx2K cameras will capture planes where the highest resolution is needed.

Velocity Profiles From Phosphorescence

Phosphorescence can also be used to do time-line photography based on the same principles as hydrogen bubble flow visualization done with heated wires in water tunnels. The flow is seeded with a cloud of phosphorescent material. The laser beam is directed along a selected line in the flow, so that all the seeding along the line starts phosphorescing. Three cameras are set up in the flow-field at appropriate locations. The cameras are triggered externally to open a fixed time period after the laser tags a line in the flow. The camera gating duration is set to capture streaks. The deformation of the phosphorescent line with respect to the tagged line will give the velocity profile in 3-dimensions. A schematic is shown in Figure 1. The table below lists the characteristics of a number of commonly available dyes. Note the wide range of excitation frequencies and lifetimes.

Table 1: Characteristics of commercially available dyes. From Refs. 12 - 16

Item	Name of dye	Excitation(nm)	Emission(nm)	Lifetime
1	Flourescein	494	518	4.96ns
2	Alexa 488	495	519	~ 5 ns
3	Rhodamine B	555	580	6.16ns
4	Europium chloride	556	575	0.1 ms
5	Acetophenone	387	~420	~5ms
6	Benzophenone	412	~450	~8ms
7	La Jolla Blue	680	700	~ 4.5ns

The acquisition procedure is quite efficient. The laser flashes will be set to occur nominally at 70 times per second to coincide with each blade passage of the two blades, and then the time between flashes will be increased by 7.57 microseconds so that each blade passage is illuminated 1% of chord downstream of the previous flash. The fluorescence measurement region will be kept constant and the images recorded for about 30 seconds. The plane is then moved downstream in steps so that the entire process is repeated for 30 seconds at each such measurement station.

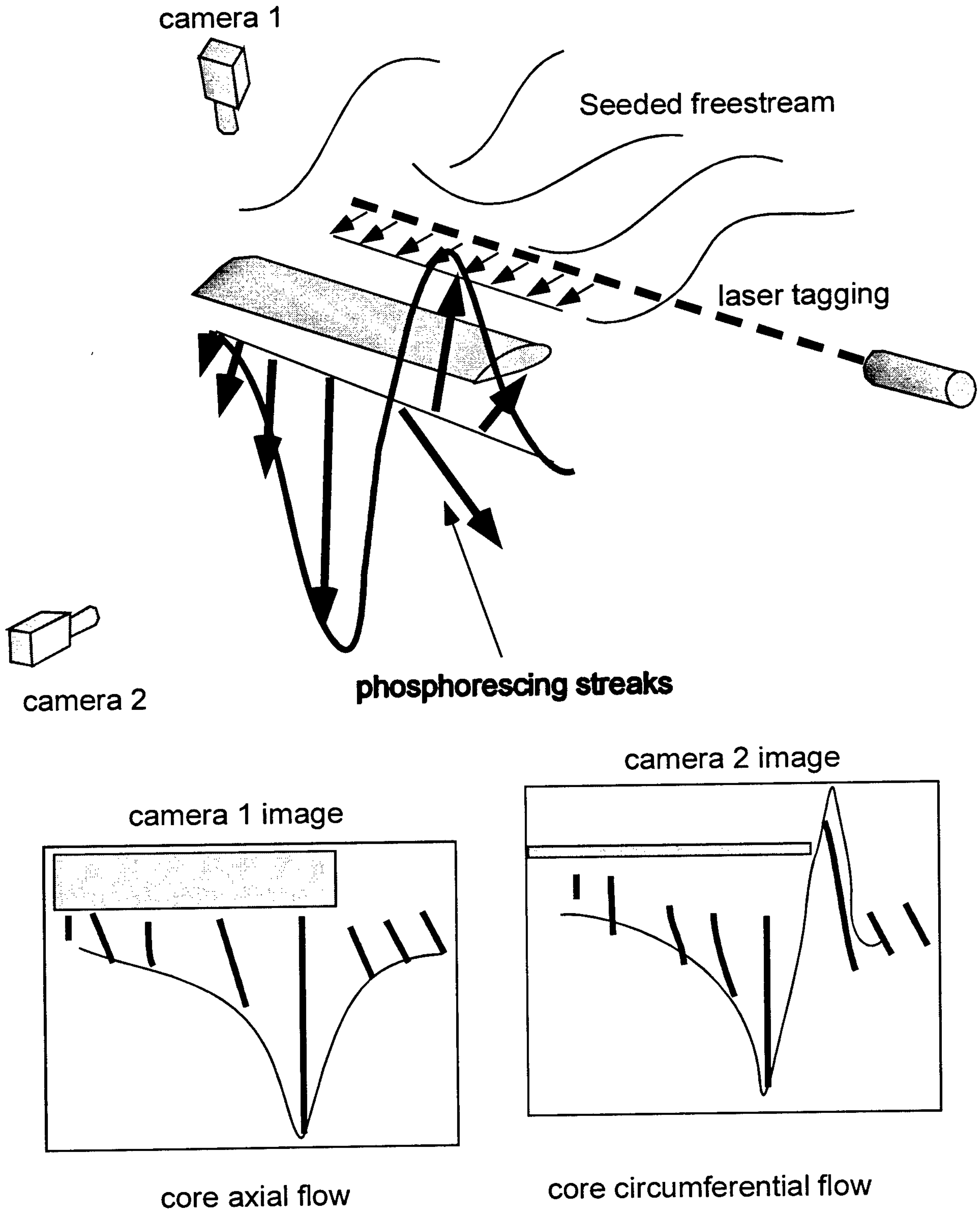

Figure 1. Measurement of velocity profiles using phosphorescence tagged time-lines

On videotape, this sequence will resemble a very slow motion of the rotor blade. Our operating experience with this 2-bladed rotor and visualizations of its wake show that the rotor speed control and the flow quality are quite adequate to achieve the periodicity needed to make this process work. The recorded video will be captured as movies into an SGI O2 workstation, and sorted according to rotor blade station. By locating the centroid of the light intensity, the trajectory of the fluid element originating from each chordwise station will be captured. At the end these will be reconstructed into a 3-D flowfield, with colors used to distinguish filament trajectories from each chordwise station. If the intensity level permits, we will attempt to capture the fluid motion using a pair of intensified, time-separated video cameras to determine the in-plane velocity field. This is discussed further in a following section.

2.2.2 Passive Scalar Visualization Using Mie Scattering

In the above problem, Mie scattering from seed particles is easily captured in planes illuminated by a 532nm sheet. The light sheet achievable with this system is an order of magnitude more intense and precise than that from the copper vapor laser; the pulse energy is as much as 40 times that from the CVL. Thus the scattering intensity from each particle illuminated in the sheet is expected to be 2 to 3 orders of magnitude brighter than from the CVL sheet. Imaging at the distances, flow speeds and time scales of rotor tip vortex development requires much greater pulse energy, and shorter exposure, than what can be obtained with the CVL and home camcorders. We aim for better resolution in imaging the rotor tip vortex core, at tip speeds from 100 to 200m/s.

2.2.3 Spatial Correlation Velocimetry

The fluorescence or phosphorescence images obtained from two time-separated cameras are used to compute the instantaneous in-plane velocity field by direct spatial cross-correlation. When Mie scattering is used, the 532nm beam will be split into two and one beam will be time-delayed to enable double-camera imaging: a suitable delaying mechanism has to be found for this. With the requested equipment, spatial cross-correlation velocimetry (SCV, [20]) will be performed using the 2-camera system. In SCV, we need not resolve particles: thus, the temporal evolution of spatial patterns of fluorescence or phosphorescence, seen by two time-separated gated cameras, can be used for velocity measurement. The high resolution of the cameras provides excellent spatial resolution. This potentially allows extension of the SCV technique down to the smallest scales of turbulence in the flow.

2.2.4 Planar Doppler Velocimetry

The pulse intensity of the requested laser is adequate to enable sensing of the Doppler shift from cross-flow laser sheet images of Mie scattering. Here one of the cameras will be used for the reference image, and the other for sensing the image filtered through a notch filter set at the incident laser frequency. This method has been used at Langley by Gorton et al [19]. Alternately, following the method of Ref. [17], one of the cameras can be used to capture two split images, freeing the other camera to capture another component of the velocity. Cross-flow vortex images permit easy interpretation of flow direction, so that even one camera can be used, with knowledge of the shape and center of the vortex from the image, to capture the 2-component velocity distribution. This is adequate for measuring instantaneous vortex strength, and its changes during, for example, forebody vortex control experiments. One advantage of PDV is that a single laser flash can give the velocity, permitting use of the video-rate laser, rather than a high frequency or double-pulsed laser. The other is that it enables studies of vortices at high tunnel speeds where usual Mie scattering visualization is quite difficult. PDV accuracy gets better as the velocity increases: Ref. [18] cites accuracy better than 2m/s in low-speed flows. Combined with SCV (using the copper vapor laser), we can thus put together a comprehensive diagnostic capability spanning the entire speed range.

2.3 Benefits to on-going research projects

2.3.1 The Origin and Structure of Trailing Vortices in Aerodynamics. Army Research Office / Ohio State U. (T.Doligalski / A. T. Conlisk)

We are attempting to capture the detailed mechanisms by which a rotor blade tip vortex originates, and its detailed structure immediately thereafter. This is motivated by the apparent discrepancies between observations (and predictions) of the structure of tip vortices from various types of blades and wings, and the possibility of resolving these by pursuing high-fidelity matching of analysis and experiment on basic test cases which incorporate the required phenomena. One of the experimental cases studied is a square-tipped rotor blade in forward flight. The vortex system from this rotor and its effects on surfaces have been extensively studied, and used as a test case to make progress in analytical prediction. These predictions have now confirmed the crucial role of the axial velocity in the vortex core, leading to the question of how the core is formed. By tracing the origin of the vortex unambiguously, at the tip of a rotor blade, we expect to identify the precise mechanism whereby the core structure is determined. We believe that these studies can provide the links between observations on rotor blade tips of various shapes, fixed-wing vortices, and the vortices observed over sharp-edged swept wings and forebodies at angle of attack. The ability to capture vortex filaments as they lift off the blade surface is crucial to these studies, and the proposed systems will make a major difference to the payoff from this project. These measurements will be merged with many other pieces of the puzzle: wake vortex trajectories, periodic velocity field in the wake, velocity profile measurements in the vortex after it has been formed, the structure of the counter-rotating vortex and the edge of the inboard vortex sheet, and measurements of the blade tip pressure distribution.

2.3.2 Near Wake Measurement. Rotorcraft Center of Excellence (NRTC; Dr. Yung Yu, NASA, and Dr. T.Doligalski, Army Research Office)

Here the structure and evolution of the vortex-dominated wake of a rotor is studied both analytically and experimentally. The region of interest goes well beyond the immediate vicinity of the blade, and onto the first 2 turns of the vortex spiral, including the region where blade-vortex interaction commonly occurs. The experiments use velocity measurements using laser Doppler velocimetry, vortex tracking in several facilities, and some inflow measurements as needed to tie the predictions to the measurements. The results are to guide the development of low-noise rotors using validated aeroacoustic predictions, and to verify the flow features of selected low-noise tip designs. Again, the issues include the turbulence effects and the diffusion of vorticity postulated by some researchers, and the evolution of the vortex core structure. Using Mie scattering Doppler velocimetry, it is difficult to answer these questions definitively, so that true fluid velocity measurement is needed. This will be attempted using gas-phase LIF. The proposed system offers major benefits in extending strobed wake visualization to higher speeds, enhancing resolution of the roll-up processes, and, with the long-life phosphorescence technique, enable 3-dimensional, time-resolved definition of the wake structure for several turns.

2.3.3 Wake-Lifting Surface Interaction with Active Flow Control. (NRTC: Drs Yu and Doligalski)

This Task seeks to improve understanding of the 3-D, periodic interaction of a rotor wake with a wing to a sufficient level to permit usage of the flow to alleviate download and augment aircraft control response in gusts. The aerodynamics issues include quantifying the 3-D vortex-dominated flow, and 3D separation/reattachment, before going on to study why particular control devices work. The fundamental barriers are in understanding of 3-D unsteady separation and vortex-surface interaction, rapid, efficient quantification of 4-D vector fields over large volumes and periodic flow control applied to such flows. Using the SCV technique, we have succeeded in demonstrating measurement of the periodic, 3-D velocity variation over the entire volume of the wake/wing interaction [20]. The 3rd component of velocity (spanwise), provides a tough test of the technique, since it is obtained by a 2nd-order numerical solution from the data interpolated from 27 chordwise planes of 2-D vectors. Recently, tuft visualizations have provided dramatic support for these results. This is an exciting breakthrough, but the spatial and temporal resolution need improvement: the proposed laser/camera system provides the answer.

2.3.4 Measurement Technology for Rotorcraft in Ground Effect. (NRTC)

This task develops the advances in measurement technology needed to enable progress in real rotorcraft development problems, where ground-vortex interactions, large-scale non-periodicity and vehicle maneuvers must be dealt with. The approach is to use the precise, controlled diagnostics in our wind tunnels to develop and validate measurement techniques which can be taken to large facilities elsewhere, then bring back the results and verify the suspected phenomena using further controlled experiments. A major success has been the development of a pulsed white light sheet illumination system which has enabled the first successful capture of velocity fields in complex, large-scale experiments using tiltrotor vehicle models at BHTC and the Boeing VTOL tunnel, and using a 7-ft. diameter rotor in a 30' x 30' settling chamber at Ames Research Center [3]. The technical challenges included development of the knowledge needed to use portable, inexpensive systems to perform diagnostics with the needed accuracy. Again, the requested system allows, for the first time, the illumination of large-enough areas (in safe facilities) to permit direct comparison and calibration of the white-light system.

Other projects being pursued here include the measurement of forces and associated flowfields on micro air vehicles during arbitrary high-rate maneuvers, and the study of why a Stagnation Point Vortex Controller [5] works so well in controlling forebody vortex asymmetry on models of missiles and aircraft. The very high beam quality of the Infinity laser at 532nm, combined with the 1 to 2 ns pulse time, enable excellent spatial and temporal resolution.

2.4 Synergy of Research and Instruction: the ILID experiment

The Experimental Aerodynamics Research group at our School has the distinction of having won the Georgia Tech Sigma Xi's Outstanding PhD Thesis Award (won by 1% of GT theses, selected by an Institute faculty committee each year) *for 3 of our last 6 theses.* At the same time, we are privileged to have the enthusiastic participation of approximately ten undergraduates each year, including freshmen through seniors, each bringing a unique set of interests and skills. It is interesting to note that these students are walk-ons, recruited on the basis of enthusiasm for hands-on work, yet their average academic GPA is a stellar 3.6+. The group now has 5 PhD candidates and 3 M.S. candidates, all of whom have become familiar to some extent with the principles, operation and maintenance of the argon ion lasers and the copper vapor laser. Thirteen 13 PhDs, 25 M.S. and 70+ undergraduate students have worked with us in the past 13 years; at present there are 12 undergraduate assistants, several of them Co-Op students.

Phase I: Flow Imaging and Control Laboratory course development:

The P.I. has used an NSF Leadership in Laboratory Development grant (1992) to develop multimedia-based course material as a prototype for educating students in fluid mechanics with substantial reliance on experimental methods. He developed 4 unique courses on Advanced Flow Diagnostics and Flow Control Techniques, drawing on the help of the students in the labs and in the courses themselves. These courses, tailored to either the undergraduate senior level (AE4xxx) or graduate elective level (AE8xxx), have been taught about 4 times each. This produces a small by very special group of students each year who have learned to solve problems using digital images and techniques in experimental fluid dynamics and aerodynamics. The first phase of this project was completed in 1995, with image sequences obtained using the copper vapor laser in research projects being transferred into problem sets used in graduate and undergraduate classes.

Phase II: Iterative Learning Through Integration of Disciplines (ILID):

A new phase is underway at present, with courses being converted to Web-based form, built around a freshman-level Introduction to Aerospace Engineering. With large storage resources, fast computers and a new 10MB/s network link, conversion of research images into widely disseminated course material is picking up speed again. With this new laser / camera system we can perform video-rate high-intensity flow imaging, enabling us to capture elusive dynamic phenomena with a clarity adequate for conversion to course material. This effort aims to integrate the curricula tightly with the research knowledge base, with speed-of-thought access to information across levels and disciplines. Advanced flow diagnostics constitute one of the most versatile of cross-disciplinary endeavors, drawing on the best ideas of every scientific discipline.

Phase III: The Aerospace Digital Library:

The ILID nucleus being developed around the flow diagnostics curriculum forms the center of an ambitious effort to integrate research and instructional resources into an Aerospace Digital Library. Again, a crucial element of this centers on advanced flow diagnostics: the techniques and publications of the AIAA's Aerodynamic Measurements

Technical Committee are being integrated by our group into a coherent, versatile knowledge base. Thus the products from the proposed diagnostic equipment will go into the core of a growing knowledge base.

2.5 How the Proposed System Fits in

This system is proposed as the next step in a program which has led the development of measurement technology for rotorcraft and wind tunnel applications. Such a versatile and powerful system will find many applications.

The first 5-watt laser purchased here in 1982 was intended to power a laser velocimeter in the 9-foot hover facility. In practice, it served in 4 facilities, and opened up the major benefits of laser sheet imaging, which was used to quantify the rotor-airframe interaction thoroughly using a strobed technique. Other argon lasers have added to these capabilities, and both LDV and strobed light sheet techniques have become quite routine.

In 1988-89, an ARO DURIP grant gave us the copper vapor laser, intended to attempt planar velocimetry by direct cross-correlation of flowfield smoke patterns. At the time, PIV (Particle Image Velocimetry) used double-pulsed transparencies and fringe post-processing, with direct computational cross-correlation ruled out as prohibitive. Spatial Correlation Velocimetry, U.S. Patent 5,249,238, showed the way to obtain velocity fields without the need to resolve individual particle scattering. Using inexpensive cameras, we have since been able to capture and quantify unsteady velocity fields in very complex rotorcraft problems, involving out-of-plane flow and strong vortices. The decision to keep the equipment cost level low during algorithm development paid off as we demonstrated, in just the last year, usage of a white-light system at 3 major rotorcraft facilities, each conducted as a 1-week-from-set-up-to dismantling operation. We are able to extend the SCV technique down to the fine-scale of expensive dual-laser PIV (as demonstrated by analyzing 4K x 4K images from Wright Labs cameras [21] recently), or to the simplicity of undergraduate experiments on water flow behind cylinders (routinely done since 1992, [22]), with the same confidence as to the immense distances, hostile environments and out-of-plane flowfields of full-scale rotorcraft facilities.

The copper vapor laser also allowed a major step in rotorcraft interactional aerodynamics by showing, through a dynamic image sequence, the interaction of a rotor wake with the separated flow behind a backward-facing step on an airframe. What had appeared to be a huge problem turned out to a very direct problem.

At present, we have reached the limits of what can be done with copper-vapor or argon-ion lasers. Pulsed Nd-YAG lasers are now available at moderate cost to perform PIV at video rates; we are attempting to obtain these under institutional funding for routine usage. This will, however, not provide the tunable wavelengths needed to do fundamental fluid mechanics problems such as those in the generation of the rotor tip vortex.

Table 1: History of Class IV Laser Operations in the Experimental Aerodynamics Group

Laser and sponsor	Uses & operating facilities	Knowledge contributions / problems solved
5-watt cw argon ion, 1982 (ARO,	LDVand laser sheet in 9' hover facility,	1. Tip vortex core in hover. 2. Rotor-airframe interaction

Rotorcraft Center #1)	7x9 and 42" tunnels	3. F-15 wing and tail flowfield 4. Rotor vortex trajectories 5. Focal plane distortion of satellite-TV receivers, 6. Off-Axis Scatter Receiver invention and development.
5-watt cw argon laser, low-cost model, **1988** (ARO Rotorcraft Center #2)	LDV and laser sheet in 9' and 16' hover facilities.	1. Velocity field of Blade Tips at high pitch angles 2. Inflow to vibrating rotor blades: very-high-data-rate LDV demonstration. 3. Vortex trajectories in 16' Hover Chamber
30w, 6Khz Copper Vapor; **1988**, ARO/DURIP	Light sheet, SCV in 9' hover facility and 7'x 9' tunnel	1. Vortex-surface collisions 2. Large-area velocity measurement: SCV invention. 3. Rotor-airframe interaction with massive flow separation 4. Counter-rotating vortex at edge of inboard vortex sheet 5. Flow over a wing-body at angle of attack: vortex structure and dynamics 6. Wing-canard interaction 7. Blade tip flow at high pitch angles. 8. Rotor Wake / Wing Interaction 9. Transient 3D flow separation due to wake impingement 10. Flow over a plunging wing 11. Forebody vortex time scales 12. Cable design for low vibration. 13. Flow over automobile components. 14. Flow imaging over maneuvering fighter models using Wind Driven Manipulator 15. X-38 vortex/ flaperon interactions.
6-w cw argon; NSF-ILI, **1992**	LDV and laser sheet in 42" and 7' x 9' tunnels	1. Counter-rotating structures over delta wing: genesis of tail buffeting. 2. Flow control experiments over various models. 3. Vortex Core Axial Velocity 4. Near Wake of a rotor blade 5. Capture of parafoil transient collapse & porosity effects.

All but the last named laser have had tube replacements and other major maintenance performed. In the case of the Copper Vapor Laser, we estimated a lifetime of 5 years. The manufacturer/vendor went out of business in 1992. Operating experience with CVLs around the nation appears to be that useful life is 1-2 years. However, our student teams have set up a knowledge base and parts source network which has enabled our CVL to be run practically every other day for the last 9 years. The list of Patents, theses and publications generated, and students who learned to use these lasers is given below.

2.6 Products Enabled By Laser Diagnostics: 1982-98.

PhD Theses

T.L. Thompson "Velocity Measurements in the Tip Vortex Core of a Rotor in Hover", 1986.

S-G. Liou, "Velocity Measurements on a Lifting Rotor/Airframe Configuration in Low Speed Forward Flight", 1988.

Philip A. Fawcett, "Spatial Correlation Velocimetry", 1992. Winner, GT Sigma Xi Outstanding Thesis Award, June 1993.

Jai- Moo Kim, "The Interaction Between a Rotor Wake and Cylinder With and Without Flow Separation", 1993. Winner, GT Sigma Xi Outstanding Thesis Award, June 1994.

Robert Brent Funk, "Transient Interaction Between a Rotor Wake and a Lifting Surface", 1995.

James Paul Hubner, "An Investigation of Quasiperiodic Structures in the Vortical Flow Over Delta Wing Configurations", 1995.

John Carl Magill, "Identification and Control of Wind-Driven Dynamic Model Manipulators for Wind Tunnels". School of Electrical Engineering, 1995.

Leigh-Ann Darden, "Rolling Moment Response of a Wing-Body to Stagnation Point Actuation". 1997. Winner, GT Sigma Xi Outstanding Thesis Award, June 1998.

Urmila C. Reddy, "Three-Dimensional Velocity Field Reconstruction in Periodic Flows". In progress.

Raghavendran Mahalingam, Research Area: Vortex-Surface Collisions. In progress.

Catherine Matos, Download Reduction on a Wing in a Rotor Wake. In progress.

Mark Alan Klein, Research Area: Over Swept Wings. In progress.

Oliver Wong. Research Area: Rotor Tip Aerodynamics. In progress.

Other Student Participation

28 M.S. degrees have been earned; 70 undergraduates have participated either on Research Special Problems or as Research Assistants.

Inventions Developed Using Laser Systems

1. Komerath, N.M., and Fawcett, P.A., "Spatial Cross-Correlation Velocimeter" U.S.Patent No. 5,249,238, September 1993.
2. Komerath, N.M., Darden, L-A., Peterson. K.G., Magill, J.C., "Stagnation Point Vortex Controller". U.S. Patent 5,794,887, August 1998.

Journal Papers 1988 - 1997 Using Laser Systems.

1. Komerath, N.M., Thompson, T.L., Kwon, O.J., and Gray, R.B., "The Velocity Field of a Lifting Model Rotor Blade in Hover". Journal of Aircraft, Vol. 25, No.3, March 1988, pp. 250 - 257.
2. Brand, A.G., Komerath, N.M. and McMahon, H.M., "A Laser Sheet Visualization Technique for Incompressible Vortex Wakes". Journal of Aircraft, Vol. 25, No. 7, July 1988, pp. 667-668.
3. Komerath, N.M., Liou, S.G., Brand, A.G., and McMahon, H.M., "A Study of the Encounter Between a Helical Vortex and a Circular Cylinder". Proceedings of the AIAA/ASME First National Fluid Dynamics Congress, Vol. 2, pp. 1055- 1063, July 1988.

4. Thompson, T.L., Komerath, N.M., and Gray, R.B., " Visualization and Measurement of the Tip Vortex Core of a Rotor Blade in Hover". Journal of Aircraft, Vol. 25, No. 12, December 1988, pp. 1113 - 1121.
5. Liou, S.G., Komerath, N.M., and McMahon, H.M., "Velocity Measurements of Airframe Effects on a Rotor in Low-Speed Forward Flight". Journal of Aircraft, Vol 26, No. 4, April 1989, pp. 340 - 348.
6. Mavris, D.M., Komerath, N.M., and McMahon, H.M., "Prediction of Rotor/Airframe Aerodynamic Interactions". Journal of the American Helicopter Society, Vol.34, No.4, October 1989, p. 37-46.
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8. Liou, S.G., Komerath, N.M., McMahon, H.M.,"The Velocity Field of a Circular Cylinder in the Wake of a Rotor in Forward Flight". Journal Aircraft, 27, 9, Sep.1990, p.804-809.
9. Liou, S.G., Komerath, N.M., and McMahon, H.M., "Measurement of Transient Vortex-Surface Interaction Phenomena". AIAA Journal, Vol, 28, No. 6, June 1990, p. 975-981.
10. Sriram, P., Hanagud, S., Komerath, N.M., and Craig, J.C., " Scanning Laser Doppler Velocimeter for Measuring Beam Vibrations". Applied Optics., Vol.29, No.16, June 90, p. 2409-2417.
11. Komerath, N.M., Liou, S.G., and Thompson, T.L., "A Remote-Aligned Off-Axis Receiving System for Laser Velocimetry in Large Facilities. Experimental Techniques. Vol. 14, No. 4, July 90, 29-33.
12. Brand, A.G., McMahon, H.M., and Komerath, N.M. "Correlations of Rotor/Wake-Airframe Interactions with Flow Visualization Data". Journal of the American Helicopter Society . Vol. 35, No. 4, October 1990, p. 4-15.
13. Komerath, N.M., Mavris, D.M., Liou, S-G., "Prediction of Unteady Pressure and Velocity over a Rotorcraft in Forward Flight". J. Aircraft, Vol. 28, No. 8, August 1991, p. 509 - 516.
14. Komerath, N.M., Liou, S-G., Schwartz, R.J., Kim, J-M., "The Flowfield of a Twin-Tailed Aircraft at Angle of Attack. Part I: Spatial Characteristics". Journal of Aircraft, Vol. 29, No. 3, May-June 1992, p. 413 - 420.
15. Komerath, N.M., Schwartz, R.J., Kim, J-M., "Flow Over a Twin-Tailed Aircraft at Angle of Attack, Part II: Temporal Characteristics". J. Aircraft, Vol. 29, No. 4, July 1992, p. 553-558.
16. Affes, H., Conlisk, A.T., Kim, J.M., and Komerath, N.M., "A Model for Rotor Tip Vortex - Airframe Interaction, Part 2: Comparison with Experiment". AIAA Journal, Vol. 31, No. 12, p. 2263-2273, December 1993.
17. Kim, J-M., Komerath, N.M., and Liou, S-G., "Vorticity Concentration at the Edge of the Inboard Vortex Sheet". J. American Helicopter Society, Vol. 39, No.2, p.30-34, April 1994.
18. Liou, S-G., Komerath, N.M., Lal, M.K., "Measurements Around a Rotor Blade Excited in Pitch. Part 1: Dynamic Inflow". J. AHS, Vol. 39, No. 2, April 1994, p. 3-12.

19. Lal, M.K., Liou, S-G., Pierce, G.A., and Komerath, N.M., "Measurements Around a Rotor Blade Excited in Pitch. Part 2: Blade Surface Pressure". J. AHS, Vol. 39, No.2, p.13-20, 1994.
20. Komerath, N.M., Kim, J.M., Liou, S.G., "Rotor Wake Interaction with Separated Flow". Invited Paper, Mathematical and Computer Modelling, Special Issue on Rotorcraft, Vol. 18, No. 3/4, pp. 73-87, Pergamon Press, October 1993. (GT Sigma Xi Best Paper Award, 1994).
21. Kim, J.M., and Komerath, N.M., "Summary of the Interaction of a Rotor Wake and a Circular Cylinder". AIAA Journal Vol. 33, No. 3, March 1995, p. 470-478.
22. Komerath, N.M., "Flow Imaging and Control Laboratory: An Experiment in Iterative Learning". Annual Conference Proceedings of the ASEE, 1994, Vol. 1, p. 737-743.
23. Hubner, J.P., Komerath, N.M., "Spectral Mapping of Quasiperiodic Structures in a Vortex Flow." Journal of Aircraft, Vol.32, No. 3, May- June 1995, pp. 493-500.
24. Foley, S.M., Funk, R.B., Fawcett, P.A., and Komerath, N.M., "Rotor Wake -Induced Flow Separation on a Lifting Surface" J. AHS, Vol. 40, No.2, April 1995, p. 24 - 27.
25. Lal, M.K., Liou, S-G., Pierce, A-G. and Komerath, N.M., "Correlations of Unsteady Pressure and Inflow Velocity Fields of a Pitching Rotor Blade". Journal of Aircraft, Vol. 32, No.3, May-June 1995, p. 520 -528.
26. Magill, John C., Darden, L.A., Komerath, N.M., "Flow Visualization During Multiple-Axis Motions Using a Wind-Driven Manipulator". J. Aircraft, Vol. 33, No. 1, Jan-Feb'96, p.163-170.
27. Komerath, N.M., "Experimental Curriculum in Diagnostics and Control of Unsteady Flows". ASEE Journal of Engineering Education, June 1996.
28. Hubner, J.P., Komerath, N.M., "Counter-Rotating Structures Over a Delta Wing". AIAA Journal, Vol. 34, No. 9, September 1996, p. 1958-1960.
29. Darden, L.A., Komerath, N.M., "Relationship Between Stagnation Point Deflection and Forebody VortexAsymmetry", AIAA Journal, Dec. 1997.

Conference Papers

Over 90 conference papers have been presented on research performed using these laser systems.

Useful Life of the Requested Equipment

The useful life of the requested system is estimated to be 5 to 7 years. This is based on our record of laser operations at the Experimental Aerodynamics Group. The system will be suitable for use in 3 facilities here, and the cameras will find usage in off-site tests as well.

2.7 Ongoing support for the diagnostics research

1. "Near Wake Definition for Low Noise Rotors". NRTC RCOE Task 1.2	$623K, Jan. 96- Dec. 2000
2. "Wake-Lifting Surface Interaction With Active Flow Control". NRTC RCOE Task 9.1	$471K, Jan. 96 – Dec. 2000
3. "Measurement Technology for Rotorcraft in Ground Effect". NRTC RCOE Task 9.2	$597K, Jan. 96 – Dec. 2000
4. "Origin and Structure of Trailing Vortices" ARO/ OSU	$148K, 5/97- 4/2000
5. Delta Air Lines: Engine Test Cell Flows	$3K, July – December '98
6. Idaho National Emergency Labs: Wind Sensor dev.	$15K, March – Aug. '98

2.8 PERSONNEL

The Experimental Aerodynamics Group at the School of Aerospace Engineering is led by Professor N.M. Komerath, and at present includes Dr. Robert Funk, Research Engineer at the GTRI Aerospace and Transportation Laboratory, 6 PhD candidates, 3 M.S. candidates and approximately ten undergraduates (the number changes each quarter with Co-Op schedules). This proposal is developed by Dr. Komerath and PhD candidate Raghav Mahaligam, who is studying the measurement of the rotor tip vortex.

Narayanan M. Komerath Professor of Aerospace Engineering

Dr. Komerath received his B.Tech, A.E. at IIT, Madras in 1978, M.S.AE (Propulsion, '79) and PhD A.E. (Turbulent Combustion, '82) at Georgia Tech, where he has since worked as a Post-Doctoral Fellow (82-83), Research Engineer II (83-85), Assistant Professor, (85-89), Associate Professor (90-93) and Professor (94-). He has developed data acquisition systems and diagnostics techniques for a variety of experimental facilities for ramjet aeroacoustics, rotorcraft and fighter aerodynamics, and turbulent combustion. He has participated in the ARO Rotorcraft Center of Excellence at Georgia Tech since its inception in 1982, studying rotor tip vortices, rotor wake/airframe interactions, vortex-surface collisions, inflow to vibrating blades, and unsteady flow separation. He has taught over 1300 aerospace engineers, served as undergraduate advisor for 10 years, taught over 16 different courses in aerodynamics, propulsion, gas dynamics, measurement techniques and flow control, conducted over 50 sponsored projects, and published over 120 papers. Since 1990, he directs the operation of the John J. Harper Wind Tunnel, the 42" Low Speed Tunnel and the 9-foot rotor hover facility. He served as a member of the AHS Aerodynamics Technical Committee ('93-96) and the AIAA Aerodynamic Measurement Technical Committee ('94-present).

Patents

1. Komerath, N.M., Fawcett, P.A., "Spatial Cross-Correlating Velocimeter". U.S.Patent 5249,238, Sep93.
2. Magill, J.C., Komerath, N.M., "Wind-Driven Dynamic Manipulator". U.S. Patent 5345,818, Sep.94.
3. Komerath, N.M., Darden, L.A., Peterson, K.P. and Magill, J.C., "Stagnation Point Vortex Controller". U.S. Patent 5,794,887, August 1998.

Recent Publications

Hubner, J.P., Komerath, N.M., "Counter-Rotating Structures Over a Delta Wing". AIAA Journal, September 1996.

Magill, John C., Komerath, N.M., Dorsey, J.F., "Experimental Evaluation of an Adaptive Controller for a Wind Driven Pitch Manipulator". AIAA Journal of Guidance, Dynamics and Control, January 1996.

Magill, J.C., Darden, L.A., Komerath, N.M., "Flow Visualization of Maneuvers Using a Wind-Driven Dynamics Manipulator". AIAA Journal of Aircraft, January 1996.

Magill, J.C., Komerath, N.M., "Wind-Driven Dynamic Manipulator for Wind Tunnels". Experimental Techniques, Vol. 19, No. 1, Jan.-Feb. '95, p. 27-30.

Kim, J.M., and Komerath, N.M., "Summary of the Interaction of a Rotor Wake and a Circular Cylinder". AIAA Journal Vol. 33, No. 3, March 1995, p. 470-478.

Komerath, N.M., "Flow Imaging and Control Laboratory: An Experiment in Iterative Learning". Ann. Conf. Proc. of the Am. Soc. of Engg Education, 1994, Vol.1, p. 737-43.

Hubner, J.P., Komerath, N.M., "Spectral mapping of quasi-periodic structures in a vortex flow." Journal of Aircraft, Vol.32, No. 3, May-June 1995, p. 493-500.
Foley, S.M., Funk, R.B., Fawcett, P.A., and Komerath, N.M., "Rotor Wake-Induced Flow Separation on a Lifting Surface" J. Am. Helicopter Soc., 40, 2, April 95, p. 24 - 27.
Lal, M.K., Liou, S-G., Pierce, A-G. and Komerath, N.M., "Correlations of Unsteady Pressure and Inflow Velocity Fields of a Pitching Rotor Blade". J. Aircraft, 32,3, May 95, p.520 -528.
Darden, L.A., Peterson, K.G., Komerath, N.M., "Roll Control Using a Stagnation Point Actuator" AIAA Paper 96-2498, AIAA Applied Aerodynamics Conference, June 1996.

Honors

1. Most Valuable Professor Award, GTAE Class of 1991.
2. Georgia Tech 1993 Leadership Award for Development of Graduate Research Assistants.
3. Georgia Tech Sigma Xi 1993 Award for Advisor of Outstanding PhD Thesis (J.M. Kim).
4. Georgia Tech Sigma Xi 1994 Award for Advisor of Outstanding PhD Thesis (P.A. Fawcett).
5. Georgia Tech Sigma Xi 1994 Faculty Best Paper Award.
6. National Science Foundation Leadership in Laboratory Development Grant, 1992-95.
7. Georgia Tech 1997 Institute Award for Outstanding PhD Thesis Advisor, 1992-97.
8. Georgia Tech Sigma Xi 1998 Award for Advisor of Outstanding PhD Thesis (L.A. Darden).
9. Associate Fellow of the AIAA since 1993.

Raghav Mahalingam   Doctoral Candidate, Aerospace Engineering

Raghav Mahalingam received his B.Tech, A.E. at the Indian Institute of Technology, Madras, in 1994, M.S.A.E (Aerodynamics) in 1995 at Georgia Tech and is currently a doctoral candidate and graduate research assistant in A.E.. He has had experience with various diagnostic techniques including laser Doppler velocimetry, laser based flow visualization, steady and unsteady pressure sensing techniques and hot-film anemometry. He has also developed data-acquistion and analysis codes using cross-language interfacing. He has been part of the RCOE at GaTech since 1994, studying vortex-wing, rotor-cylinder and rotor-wing interactions. He has worked on the Experimental Aerodynamics Teams which acquired SCV, flow-visualization and hot-wire data in industrial and government facilities. He has led a team of students in conducting tests on the Experimental Crew Return Vehicle and Parafoil Landing System. He has developed a wind-tunnel wall-adaptation scheme being currently used at IIT, Madras for active wall adaptation. He has received merit citations in the Mathematics Olympiad conducted by IAMT (Indian Association of Math Teachers) in 1988 and 1989. He is a member of AIAA , AHS, SAE.

Publications and Presentations

Mahalingam, R., Funk, R.B., Komerath, N.M., " Low Speed Canard-Tip-Vortex Airfoil Interaction", SAE Paper No. 971469, selected for Publication in the SAE Transactions 1997.
Mahalingam, R., and Komerath, N. M., " Characterization of the Near-Wake of a Helicopter Rotor in Forward Flight", accepted for presentation at the 29th AIAA Fluid Dynamics Meeting , June 1998, Albuquerque, NM.

Mahalingam, R., and Komerath, N. M., " Measurements of the Near-Wake of a Helicopter Rotor in Forward Flight", AIAA Paper 98-0692, 36th AIAA Aerospace Sciences Meeting , January 1998, Reno, NV.

Mahalingam, R., Komerath, N. M., Funk, R. B., and Kim, J. M., " Three-Dimensional Vortex Surface Interactions", Proceedings at the 7th Asian Congress of Fluid Mechanics, December 1997, Madras, INDIA.

Mahalingam, R., Komerath, N. M., Radcliff, T., Burggraf, O. R., and Conlisk, A. T., " Vortex Surface Collision : 3-D Core Flow Effects", AIAA Paper 97-1785, 28th AIAA Fluid Dynamics Conference, June 1997, Snowmass, CO.

Mahalingam, R., Funk, R.B., Komerath, N.M., " Low Speed Canard-Tip-Vortex Airfoil Interaction", presented at the 1997 SAE General , Corporate, and Regional Aviation Meeting and Exposition, April 1997, Wichita,KS .

Mahalingam, R., Komerath, N.M., "Rotor Tip Vortex Collision Features", AIAA Paper 96-2013, 27th AIAA Fluid Dynamics Conference, New Orleans , LA, June 1996.

Mahalingam, R., Funk, R.B., Komerath, N.M., " Flow Visualization of Low-Speed Perpendicular Vortex-Airfoil Interaction", AIAA Paper 96-2387, Proceedings of the 14th Applied Aerodynamics Conference, New Orleans, LA.

Mahalingam, R., Peterson, K.G., Funk, R.B., Komerath, N.M., Conlisk, A.T., " Recent Experiments on Vortex Collision with a Cylinder", Invited Paper, AIAA Paper 95-2236, 26th Fluid Dynamics Conference, San Diego, CA, June 1995.

Jain, R., Conlisk, A. T., Mahalingam, R., and Komerath, N. M., " Interaction of Tip-Vortices in the Wake of a Two-Bladed Rotor", 54th Annual AHS Forum, May 1998, Washington D.C.

Matos, C. A., Mahalingam, R., Ottinger, G., Klapper, J., Funk, R. B., and Komerath, N.M., " Wind Tunnel Measurements of Parafoil Geometry Aerodynamics", AIAA Paper 98-0606, 36th AIAA Aerospace Sciences Meeting , January 1998, Reno, NV.

Reddy, U. C., Matos, C. A., Mahalingam, R., Funk, R. B., Komerath, N. M., " Velocity Measurement in a Rotor Wake Interacting with a Fixed Wing", AIAA Paper 98-1033, 36th AIAA Aerospace Sciences Meeting , January 1998, Reno, NV.

Caradonna, F., Henley, E., Silva, M., Huang, S., Komerath, N., Reddy, U., Mahalingam, R., Funk, R., Wong, O., Ames, R., Darden, L., Villareal, L., Gregory, J., " An Experimental Study of a Rotor in Axial Flight", AHS Technical Specialists' Meeting for Rotorcraft Acoustics and Aerodynamics, Williamsburg, VA, October 1997, submitted to AHS Journal.

Reddy, U. C., Moseley, C. A., Mahalingam, R., Komerath, N. M., " Whole Field Velocity Measurement in Unsteady Periodic Flows", AIAA Paper 97-2325, Proceedings of the 15th AIAA Applied Aerodynamics

2.9 References

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2. Conlisk, A.T., Komerath, N.M., "Vortex-Surface Collisions". Final Report, U.S. Army Research Office Contract DAAH04-93-G0048, March 1998.
3. Carradonna, F., Henley, E., Silva, M., Huang, S., Komerath, N., Reddy, U., Mahalingam, R., Funk, R., Ames, R., Darden, L., Villareal, L., Gregory, J., Wong, O., "An Experimental Study of a Rotor in Axial Flight". AHS Specialists' Meeting on Aerodynamics and Aeroacoustics, Williamsburg, VA, October '97. Accepted for publication by the AHS Journal.
4. Jain, R., Conlisk, A.T., Mahalingam, R., Komerath, N.M., "Interaction of Tip-Vortices in the Wake of a Two-Bladed Rotor". Proceedings of the 54th Annual Forum of the American Helicopter Society, Washington DC, May 1998
5. Darden, L.A., Komerath, N.M., "Aircraft Control Using Stagnation Point Displacement". SAE Paper 97 WAC-81, 2nd World Aviation Congress and Exposition, Los Angeles, CA October 1997.
6. Darden, L.A., Villareal, L., Komerath, N.M., "Time Scales of Forebody Vortex Response". AIAA 97-2061, 4th AIAA Shear Flow Control Conference, Snowmass, CO, June 1997.
7. Komerath, N.M., "Development of Narrow-Band Velocity Fluctuations in Vortex Flows". AIAA 95-2304, 26th Fluid Dynamics Conference, San Diego, CA, June 1995.
8. Klein, M.A., Komerath, N.M., " Reduction of Narrow-Band Velocity Fluctuations Over an Aircraft Model". AIAA Paper 97-2266, 15th Applied Aerodynamics Conference, Atlanta, GA July 1997.
9. Komerath, N.M., Matos, C., Ames, R., Mahalingam, R., Funk, R., "Low-Speed Aerodynamics of the NASA X-38 Experimental Crew Return System". Final Report on NASA Johnson Space Center Grant NAG-9-927, April 1998. http://www.ae.gatech.edu/research/windtunnel/project/e16n63/summary.html
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12. Becker, R.S., "Theory and Interpretation of Fluorescence and Phosphorescence". Wiley-Interscience.
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16. "Handbook: New Protein Labeling Kits": http://www.probes.com/handbook/tnotes/
17. Clancy, P., Samimy, M., "Multiple-Component Velocimetry in High-Speed Flows Using Planar Doppler Velocimetry". AIAA 97-0497, January 1997.

18. McKenzie, R.L., "Planar Doppler Velocimetry Performance in Low-Speed Flows". AIAA 97-0498, January 1997.
19. Gorton, S.A., Meyers, J.F., Berry, J.D., "Laser Velocimetry and Doppler Global Velocity Measurements of Velocity Near the Empennage of a Small-Scale Helicopter Model. Proceedings of the 53rd Annual Forum of the American Helicopter Society, May 1997.
20. Reddy, U.C., Komerath, N.M., "Whole-Field Velocity Measurement for Rotorcraft Aerodynamic Interactions". Proceedings of the 54th Annual Forum of the American Helicopter Society, Washington DC, May 1998.
21. Gogineni, S., Visbal, M., Shih, C., "Experimental and Numerical Investigation of Transitional Plane-Wall Jet"" AIAA 97-0071, January 1997.